PROSPECTIVE ISSUES IN SIMULATION MODEL COMPOSABILITY: BASIC CONCEPTS TO ADVANCE THEORY, METHODOLOGY AND TECHNOLOGY

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ABSTRACT

Model composability is a longstanding challenge within the simulation modeling community. While some engineering disciplines successfully apply the component-based approach to build systems, it has proven significantly difficult to apply in simulation model development. This paper presents basic concepts related to composability to layout emergent prospective issues with regard to composability. Given this basic conceptual frame, a three-tier strategy is suggested to advance the composability infrastructure. Advances in the infrastructure are predicated on the developments in theory, methodology, and technology. Better understanding of the conceptual models of composable simulations is argued to be critical in improving the technology for composition. In particular, making context a significant component of such a conceptual model, and capturing, packaging, and distribution of the context is suggested to improve qualification of simulation models for composition. The notion of an agent-mediated model base technology that uses intelligent matchmaking and brokering mechanisms to operate on such context specification objects is suggested.

1. BACKGROUND ON COMPONENTS IN ENGINEERING

In engineering systems, hardware assembly (composability) is paramount but not universally realizable. The non-universality is typical in a systems approach. For example, the assembly of the "best" engine, the "best" body, the "best" wheels, and the "best" brake system not only does not end up with the "best" car, but components may be completely incompatible. Hence, the assembly may not be realizable at all. And if by some coincidence, the assembly is physically realized, the performance of the assembly may be far from being acceptable with respect to the requirements of intended users.

In engineering applications, the selection of a hardware component cannot be done by functionality alone. There are compatibility standards and each component is labeled accordingly. This type of labeling (or documentation) can be named semantic labeling and has a cardinal role in selecting a hardware component. Furthermore, a given hardware component may be interchangeable with a set of other components. This type of knowledge is also well documented for hardware interchangeability (substitutability). Hence, semantic labeling is necessary for pertinence (applicability) as well as interchangeability. Hence, the success of some engineering fields, such as mechanical and electrical, rely on composability and interchangeability (substitutability) of components into workable systems and by nesting, to the realization of systems of systems where components are also systems. However, hardware composability and interchangeability

1. REPORT DATE **SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **MSIAC Journal. Volume 2, September 2006**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Modeling and Simulation Information Analysis Center (MSIAC),1901 N. Beauregard Street Suite 500,Alexandria,VA,22311**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT **Same as Report (SAR)**	18. NUMBER OF PAGES **18**	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**			

require a disciplined approach in developing hardware components and labeling (documenting) their characteristics with great care. A warehouse of hardware components without any proper documentation about their usability and compatibility may not be sufficient for successful practice of component-based engineering. Similar considerations should be taken into account for successful practice of model composability.

Nayak's 1995 ACM Distinguished Dissertation showed that the general model selection problem for application composition is NP-hard (Nayak 1992). Others have shown that deciding whether an identified collection of submodels meet a stated set of objectives is an NP-complete problem (Page and Opper 1999, Petty et al. 2003). Currently faced difficulties of simulation model composability as well as worst-case theoretical limitations on automated model selection (Levy et al. 1997) should not be deterrent factors for model composability. Rather, necessary studies such as found in (Davis and Anderson 2003) should be conducted to overcome the apparent difficulties. At one stage of the maturity of modeling and simulation field, some systems were (erroneously) labeled as ill-defined systems. However, relentless studies have been influential in the advancement of for example, human behavior modeling and simulation.

2. BASIC CONCEPTS

In general, the term "composability" is the quality of being composable and means to be capable or worthy of being composed. Similar to other terms ending with "-ability", for example acceptability, it refers to the objects to which it applies and not to the agents (a model composer – human or software) which performs necessary acts to realize the composition of models and/or model components. In simulation, three aspects of "model composability" need elaboration. These aspects are: related entities, related processes, and related characteristics (Figure 1).

2.1 Entities - Model composability is related to the following entities:

(e1) A model composed from other models or model components. (This model can be called a composed model (a synthesized model, an assembled model), or model, for short).
(e2) Models or model components from which one can compose other models (they are elements of a model base for composable models).
(e3) A model-base for models or model components from which one can compose other models.
(e4) An entity (human or preferably a software system) that composes (synthesizes) models from other models or model components. This entity can be called a model composer or composer, for short.

2.2 Processes - Model composability is related to the following processes:

(p1) Labeling of the models and model components in the model base prior to any search. Semantic labeling would entail, among other things, specification of the intention (or goal, or aim) for the use of the model, applicable assumptions, constraints, etc. For a model component, semantic labeling may necessitate its nature (e.g., variable, constant, parameter, state transition function, output function, etc.); for a variable, one can specify its type (input, output, auxiliary variable; if applicable, physical units, upper and lower acceptable values; for state variables, default initial conditions, etc.)
(p2) The process of formulation of a set of search criteria – based on the intention or the goal of the user – to detect relevant models and/or model components in the model base,
(p3) Searching the model base according to the search criteria. (This may require a semantic search engine to be developed for the model base.) The result of the search may be some plausible models and/or model components.
(p4) Selection of relevant models and/or model components after screening plausible models or model components for relevancy. This is qualification and selection.
(p5) Synthesizing a model from selected model(s) and/or model component(s). (This process can also be called model composition or model assembly).
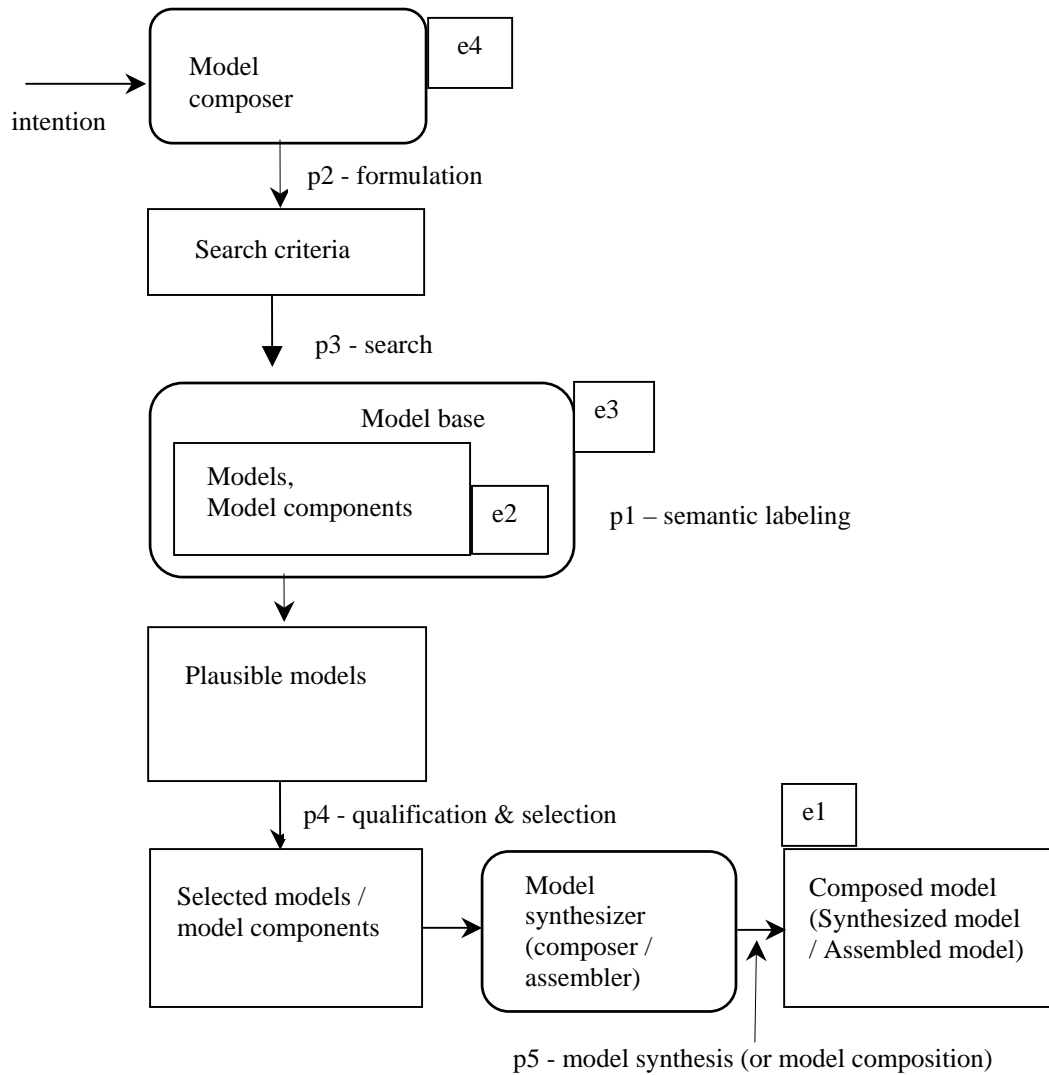
Figure 1. Entities and Processes in Model Composability

2.3 Characteristics - Model composability entails characteristics of the following entities:

(c1) Characteristics of the composed model: Within this perspective, model composability is the characteristics of a model to be synthesized (or composed, or assembled) from other models and/or model components into computationally (syntactically) and logically (semantically) coherent combinations that work together within a simulation system to satisfy the user's intentions.

(c2) Characteristics of models or model components from which one aims to compose other models: From this perspective, models and model components need to be annotated to be analyzable for the determination of possible detection, selection, and relevance assurance for model synthesis. Hence, crude legacy models may need to be preprocessed for model composability. High-level specification languages may be useful in alleviating the need of semantic labeling.

(c3) Characteristics of model bases: A model base can be used for model composability, if the models and model components it contains are annotated to be analyzable for the determination of possible detection, selection, and relevance assurance for model synthesis.

(c4) Characteristics of a model composer: A model composer needs: (1) the ability to process intention of model composition, (2) the ability to formulate a set of search criteria, (3) to access a model base of properly annotated models and model components, (4) to perform relevance assessment of plausible models and model components, and (5) the ability to synthesize (or compose, or assemble) models from selected other models and/or model components into computationally (syntactically) and logically (semantically) coherent combinations that work together within a simulation system to satisfy the user's intentions.

While engineering disciplines successfully apply component-based approach to build systems, it has proven significantly difficult to apply in simulation model development. As such, advancements in the theory, methodology, and infrastructure of simulation modeling are needed to facilitate compositional development of components of simulation studies, such as simulation models, experimental frames as well as model behavior generators and processors.

3. IMPROVING THE THEORY, METHODOLOGY, AND TECHNOLOGY OF COMPOSABILITY INFRASTRUCTURE

Improving composability through the realization of the characteristics of the entities and processes identified in section 2 require advancing the theory, methodology, and technology of simulation modeling. In particular, the following prospective issues emerge as the challenges that need to be addressed to facilitate satisfaction of the desiderata listed in section 2.3:
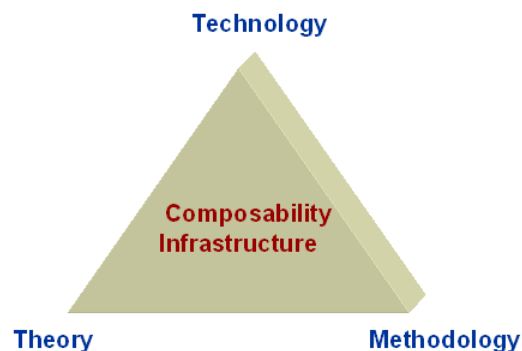
Figure 2: Components of the Composability Infrastructure

- How can we improve the technology of sharing and exchange of simulations through advanced model bases that enable intelligent brokering and matchmaking between simulation goals (intentions) and contextual (i.e., experiential, conceptual, realization) assumptions of available models?
- From a methodology point of view, what are the components of conceptual models of composable and reusable simulation models? How can contextual assumptions of components can be packaged and distributed with simulation models to facilitate high precision context-sensitive search over model bases?
- With regard to theory, are there novel design constructs (other than popular but intractable component-connector strategy) that can facilitate development of a practical and sound *model of composition*. What would be the proper underlying unified theory with uniform syntax and semantics for composition rules that can take contextual assumptions into account?

Next we elaborate on each of these issues.

3.1 Toward a Unified Theory for the Development of a Model of Composition

Model composability is defined as the characteristic of a model to be synthesized (or composed, or assembled) from other models and/or model components into computationally and logically coherent combinations that work together within a simulation system to satisfy the user's intentions. A tractable theory of composition based on a sound framework is critical for effective and practical composability.

Figure 3: Parameterized Composition

Modular compositional development of simulations requires developing simulations in terms of assemblies of standard models whose behaviors are already understood in isolation. Simulation behavior m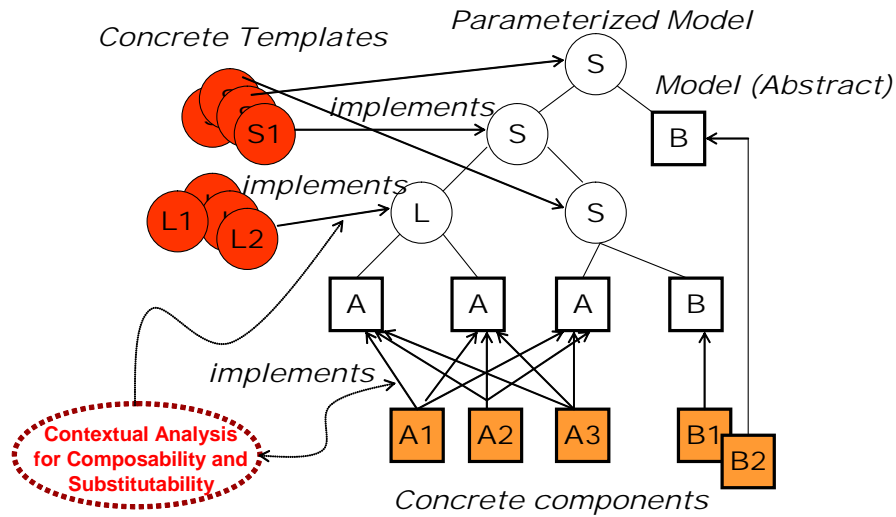ust be understood using models and their interconnections. As such, a practical approach needs to (1) describe the behavior and dependencies of each model in isolation, (2) use the dependencies among models to derive a model of the behavior of the simulation as a whole, and (3) enforce the property that behavior of the composition involves modular composition of the behavioral specification of its constituent models. This last property is needed to facilitate practical, effective analysis and predictability of compositions, as the ability to analyze quickly the behaviors of many possible alternative compositions is essential to compositional design of simulations. Yet, there are significant challenges due to the use of common component-connector taxonomy for simulation design. In particular, the component-connector strategy does not provide a unified and uniform syntax (composition rules) and semantics for composition. There are alternative strategies that have already been successful. At the very basic simulation programming level, functions are parameterized components that are instantiated by instances of their parameters. The foundations of composition via parameterization are well studied. The question is whether we can extend the granularity at which parameterization is applied (as shown in Figure 3). By viewing composition as algebra, compositions can be constructed bottom-up by binding actual parameters (model instances) to formal parameters via context and substitutability analysis. The semantics of composition can be defined as the application of the template to the specification of models that depict the semantics of individual models. Such a strategy entails development of a composition strategy that captures the properties of interest in a specific domain along with the examination of its operators and the key constants. Some models are instances whose concepts closely match the constants, whereas some are templates that characterize the operators.

3.2 The Significance of Context in Model Base Search and Model Qualification

While the significance of distinction between model, simulator, and experimental frame is clear and well documented (Zeigler at al. 2000), one of the least appreciated, but most significant aspect central to reuse is the formalization of the original context of a model. The issue of context is recognized as a significant factor in the reuse and sharing of knowledge and information (Chandrasekaran and Johnson 1993; McCarthy 1991). Situated view and use of models and knowledge, in general, places greater emphasis on the role of context. Given the fact that simulation is defined as goal-driven experimentation with dynamic models, the objectives and the context within which a simulation is originally developed becomes a critical factor in qualifying a model for composition. As such, the role and significance of context is undeniable. Context entails at least the following three dimensions: The conceptual, realization, and experimental context. The conceptual context relates the model abstraction to other concepts in the domain. More specifically, the relation defines how the semantics of the model relate to the semantics of other models in the domain of the experimental study. The realization context defines how the implementation depends on other concrete components for the completion of its definition. The conceptual and realization contexts collectively capture design dependencies. The experiential context captures the experimental conditions. Unless a simulation practitioner (1) describes a model formally to facilitate symbolic reasoning about its fitness within a new experimental frame and (2)

understands the model's contextual dependencies accurately and unambiguously, model reuse and composition will continue to be an ineffective trial-error effort. Hence, given this position, the following issues are worth exploring:

- In the context of the modeling and simulation, to facilitate the realization and maintenance of precise relations among model abstractions, simulation models, simulators, and the experimental frame, what kind of dependency conditions are of interest? What are the constituent elements of context ontology (i.e., elements of context) and their interdependencies?
- What is the best way to package and distribute original contextual information along with simulation models to facilitate improvement in understanding and sound reasoning about the fitness and suitability of a model in a new simulation context?

3.3 Agent-Mediated Model Bases for Context-Sensitive Retrieval of Simulation Models

Increased use of simulation modeling along with continuous evolution of model bases are expected to impose a burden in effective model discovery, selection, reuse, and composition. It is widely accepted that the complexity of purpose and function involves the context within which a simulation is developed, composed, and used (Davis and Anderson 2003). Since implicit assumptions significantly complicate model reuse, existing repositories need to be augmented by mechanisms that operate on models' conceptual, realization, and experiential contexts. Two emergent issues are (1) the lack of dynamic brokering mechanisms among developers and constantly evolving set of services provided by model providers and (2) the lack of high precision matchmaking methods over explicitly defined contextual model assumptions. One plausible strategy is to develop technology that promotes having model producers and consumers represented by agents providing services to one another under various forms of contracts in agent-mediated model marketplaces. In this strategy, rather than require individual agents in a model base to locate relevant models, other specially designed agents provide assistance. Matchmakers in this viewpoint are agents that maintain a continually updated repository of information about model providers currently in the system, their capabilities, and other relevant information. Agents contact the matchmaker, describing a task in the hope of finding a capable agent to assist. Brokers take this to another level of sophistication in accepting tasks from requesting agents, assigning them to others. Unlike more traditional yellow pages services, these agents can perform partial matches, providing much greater flexibility than might otherwise be available.

4. CONCLUSIONS

This paper lays out basic concepts to advance composability through progress in theory, methodology, and technology. While simulation science is founded on powerful foundations, there is still need for improvement to facilitate addressing emergent challenges of reuse and composability. As such, we delineate the requirements and characteristics of a composability infrastructure. We argue that, unlike ad hoc solutions to composability, advancements in simulation theory and methodology along with their support in the development of next generation infrastructures could provide a sound basis. To this end, a three-tier strategy is suggested: (1) development of a design for reuse methodology that facilitates (embedded) distribution of conceptual models of reusable simulations with explicit representations and constraints of conceptual, realization, and experimental context, (2) development of a unified and uniform theory of composition that uses parameterization at multiple scales and levels, where contextual analysis and parameter substitutability play key roles in composability analysis, and (3) development of an agent-mediated model base technology that uses intelligent matchmaking and brokering mechanisms that operate on context specification objects to perform context-sensitive high-precision search, retrieval, and relevance assessment for qualification of simulation models.

REFERENCES

Chandrasekaran B. and T. Johnson (1993). "Generic Tasks and Task Structures," *Second Generation Expert Systems*. Springer, Berlin, pp. 232-272.

Davis K. P. and Anderson A. R. (2003). *Improving the Composability of Department of Defense Models and Simulations*, RAND Technical report.

Levy Y.A., Y. Iwasaki, and R. Fikes. (1997). "Automated Model Selection for Simulation Based on Relevance Reasoning," *Artificial Intelligence*, Vol. 96:pp. 351–394, 1997.

McCarthy J. (1991). *Notes in Formalizing Context*. Technical report. Computer Science. Stanford University.

Nayak P.P.(1992). *Automated Modeling of Physical Systems*. PhD thesis, Stanford University, 1992

Page, E., and J. Opper. (1999). "Observation on the Complexity of Composable Simulation," In *Proceedings of the 1999 Winter Simulation Conference* , 553-560.

Petty D. M., E. W. Weisel, Roland R. Mielke (2003). "Computational Complexity of Selecting Components for Composition," *Proceedings of the Software Interoperability Conference*, 03F-SIW-073, Fall 2003.

Zeigler B. P., H. Praehofer, and T. G. Kim. (2000). Theory of Modeling and Simulation. Integrating Discrete Event and Continuous Complex Dynamic Systems. 2nd Ed. Academic Press. Davis.

TERRAIN SURFACE CODES FOR AN ALL-SEASON, OFF-RIDE MOTION SIMULATOR

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INTRODUCTION

Researchers at the US Army Engineer Research and Development Center (ERDC) and US Army Tank-Automotive Research and Development Center (TARDEC) are collaborating to improve Army ground vehicle modeling and simulation capabilities. This work, part of the US Army Science and Technology Objective (STO) #IV.GC.2003.01, "High Fidelity Ground Platform and Terrain Modeling (HGTM)", is centered on the TARDEC virtual evaluation suite [1], which includes their ride motion simulator, Figure 1. One of the goals of this effort is to embed ERDC vehicle-terrain interaction algorithms [2], within the simulator software, such that they provide the forces between vehicle components (tires or tracks) and the terrain. These algorithms need parameters associated with terrain surface conditions which are functions of weather and terrain.

This paper describes the approach taken to relate terrain mechanics properties with the terrain database, in sufficient detail to support the TARDEC Ride Motion Simulator and additionally, allow consistency when interacting with Semi-Automated Force (SAF) vehicles within the OneSAF Test Bed (OTB), OneSAF Objective System (OOS) and potentially other simulators or simulations.
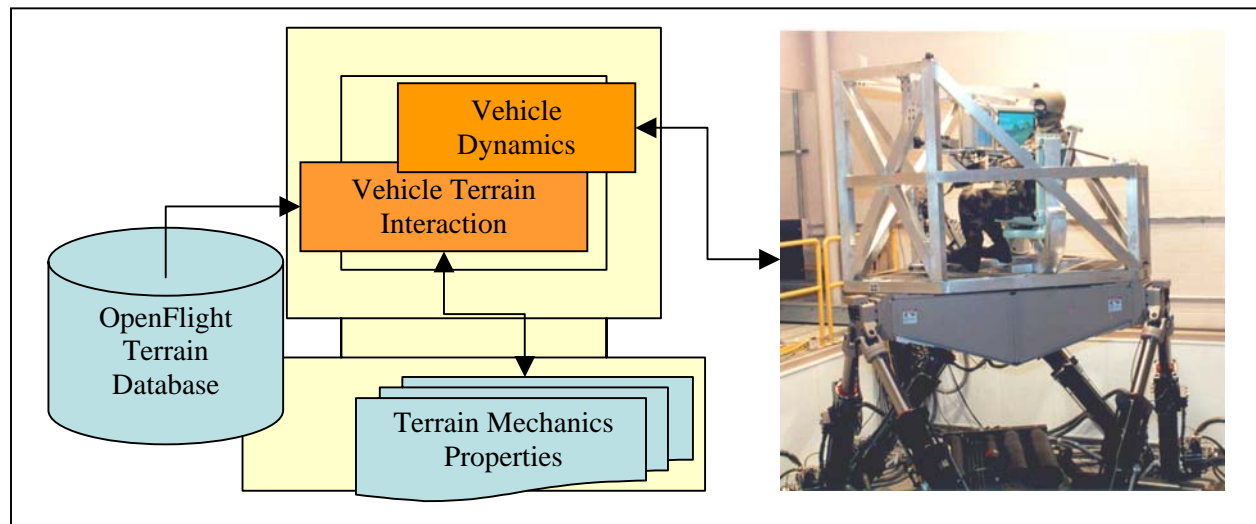
Figure 1. The TARDEC Ride Motion Simulator.

BACKGROUND

Vehicle-Terrain interaction algorithms (terramechanics software) describe how the vehicle dynamics model interacts with the terrain database. The terrain data and the Ride Motion Simulator visuals are based on an OpenFlight database. The desire is to use the OpenFlight database to store terrain attributes, which can be referenced to the parameters required by the terramechanics model. The attributes important for predicting the distribution of all-season terrain parameters are soil type, drainage, slope, aspect, canopy, and elevation. Bullock [3] developed methodology to infer soil strength values from soil type, wetness index, geographic location and a seasonal parameter (dry, average, wet, wet-wet). Following this methodology and adding capability to spatially distribute snow and thawing/frozen ground, a more distinct value of climate impact (e.g., monthly, weekly or even hourly) is indexed to a set of principal terrain mechanics parameters. Microclimate considerations suggest that soil type; wetness or drainage index, slope, aspect, and canopy should provide a unique set of indices which, when combined with climatologic and geographic information will allow estimates of the required terrain mechanics properties (Table 1). Table 1 includes the corresponding equivalent

Environmental Data Coding Specification (EDCS) attribute names and definitions, which are in the OOS terrain database.

Table 1. Terrain Mechanics Properties Required for the HGTM Terramechanics Code.

HGTM Name	EDCS[1] name	EDCS definition
Terrain condition[2] (Normal, Slippery, Frost, Snow, Ice)	SURFACE_SLIPPERY	Indication that a surface is slippery.
	FROZEN_SURFACE_COVER_TYPE	The type of frozen water present. (none, ice, snow, snow over ice, slush, etc)
Soil Type	SOIL_TYPE	The USCS soil type.
	TERRAIN_TRANSPORTATION_ ROUTE_SURFACE_TYPE	The physical surface composition of a road, runway or other surface intended to support the movement of vehicle.
Rating Cone or Cone Index at 0-6 inches	SOIL_CONE_INDEX_QB_ MEASUREMENT_DEPTH	Soil cone index at a depth: [0,15], [15,30] where measurement depths are in centimeters.
Rating Cone or Cone Index at 6-12 inches		
Snow Depth	SNOW_ONLY_DEPTH	The depth of the snow, which may be over terrain, ice or floating ice.
Snow Density	SNOW_DENSITY	The density of accumulated snow on an object.
Frost Depth	FROZEN_SOIL_LAYER_ BOTTOM_DEPTH	The depth from the terrain to the base of a layer of frozen soil.
Thaw Depth	FROZEN_SOIL_LAYER_ TOP_DEPTH	The depth from the terrain to the top of a layer of frozen soil.

[1] Environmental Data Coding Specification http://www.sedris.org/index.htm
[2] Described by more then 1 EDCS name

In order to make the terramechanics code easily updated to more complex models, and because there is not enough available storage space in the OpenFlight or Compact Terrain Database (CTDB) file formats for all these values, an index or "type" which can be related to a unique set of these values based on time of year, will allow greater flexibility to model terrain effects without the need to develop or recompile terrain databases for each desired variation in season or weather. Currently there is space in the OpenFlight format for a 16-bit integer, allowing 65535 different combinations of types. The amount of space in CTDB (version 7) is at least 512 (6 bits). The current intent is to develop the OpenFlight database and then convert it to CTDB format. This code, as an attribute to each polygon in the database will need to classify:

    1)   Soil type (23)
    2)   Drainage indices (6)
    3)   Slope and Aspect categories (27)
    4)   Canopy indices (8)

For each combination of these parameters (HGTM terrain code), within ranges of elevation, and that occur within a terrain database, there will be a corresponding set of terrain mechanics properties in a look up table (terrain mechanics properties table). This allows, for example, different tables to be developed for each month of the year (based on climatologic data for the terrain database location). Alternatively, the table could approximate the effects of a specific weather scenario, or actual measurements. Conceptually, the table could be changed during the simulation to bring in dynamic weather effects on the terrain.

The following discusses the values selected to determine this terrain attribute code.

DETERMINATION OF SOIL TYPE CODES
The Unified Soil Classification System (USCS) soil code was used to associate soil behavior to traction of vehicle for off road applications. Pavement, shallow (fordable) water and deep water are also included; discussed below are several representations, and then the scheme selected for this application.

The OneSAF TestBed operates on a CTDB, currently version 7. Describing terrain condition has been a continuous issue with the CTDB format and a review of the changes made as the CTDB evolved shows that almost every version change included a new way to represent the soil and its strength or wetness. The following was extracted from http://www.onesaf.org/extint/fdd/modsaffd.html for CTDB version 7:

"Attributes can be specified for terrain elements in addition to the SIMNET mobility index.

At a minimum, the CCTT soil type [(FACC) code (STP)], Surface Material Code (SMC), and Surface Wetness Condition (SWC) are associated with each terrain element.

Other FACC attributes can be associated with terrain using the "correction_files" mechanism of the "recompile" program.

FACC attributes of a convex polygon can be changed by the recompile program using the "correction_files" mechanism. Specified attributes are changed to the new value while other attributes of the terrain retain their original value."

Birkel [4] developed a good summary of the different soil codes available within the CTDB. Tables 2 and 3 show the codes and descriptions for SIMNET and CCTT soil codes. Additionally, during one of the Envirofed efforts [5], space was made for Cone Index 0-6, Cone Index 6-12, Soil Moisture 0-6 and Soil Moisture 6-12. These can be set using DTSIM (with JSAF), however it is not yet know if they can be set using the Terrasim software (www.terrasim.com) used to convert the OpenFlight to CTDB. Note that these 4 integers along with a soil type are used to define soil properties for use by version 1.0 of STNDMob. STNDMob (libsoilmobility) provides JVB-OTB with maximum vehicle speeds based on terrain, vehicle type and preprocessed NRMM data.

UAMBL and ERDC-GSL used 9 bits of the CTDB normally used for SIMNET soil types and CCTT soil types to allow 512 soil/terrain codes to define soil properties via a lookup table embedded in the libnrmm code (a pure C version of libsoilmobility in the UAMBL version of OTB 1.0). These terrain codes are obtained from the 9 bits in the CTDB for the cctt_simnet_soil and ctdb_soil values (cctt_simnet_soil = (ctdb_soil & 0x1ff). Table 4 shows the codes and the values developed for a specific terrain file.

Table 2. SIMNET Soil Types [4].

Index	Soil Type	Description
0	SOIL_DEFAULT	Unknown type of soil
1	SOIL_ROAD	Asphalt or other hard surface
2	SOIL_RCI250	Packed soil or dirt road
3	SOIL_RCI050	Soft sandy soil
4	SOIL_DEEP_WATER	Impassable deep water
5	SOIL_SHALLOW_WATER	Passable shallow water
6	SOIL_MUD	Muddy soil
7	SOIL_MUDDY_ROAD	Wet dirt road
8	SOIL_ICE	Slick ice surface
9	SOIL_SWAMP	Very soft surface
10	SOIL_FORESTED	Canopy or forested area
11	SOIL_US_RAILROAD	Railroad w/ US specifications
12	SOIL_EURO_RAILROAD	Railroad w/ European specs.
13	SOIL_ROCKY	Small rocks <= 18 inches
14	SOIL_BOULDERS	Large boulders 6 ft. high
15	SOIL_FLIMSY	Indoor surface for dismounted infantry
15[1]	SOIL_NO_GO	Terrain that is not traversable

[1] Note this index has two meanings, depending on the terrain database.

Table 3. CCTT Terrain Codes [4].

Terrain Code	USCS Soil Type or Surface Type	Qualitative Soil Strength	CI /RCI
1	SP, SW	Soft	35
2	SP, SW	Average	100
3	SP, SW	Hard	130
4	SM, SC, ML, ML, CH, MH, OL, OH	Very Soft	25
5	GW, GP, GM, GC, SM, SC, CL, ML, CH, MH, OL, OH	Soft	35
6	SM, SC, CL, ML, CH, MH, OL, OH	Average - Soft	50
7	SM, SC, CL, ML, CH, MH, OL, OH	Average - Hard	80
8	SM, SC, CL, ML, MH, OL	Hard	130
9	GW, GP, GM, GC, SM, SC, CL, ML, MH, OL	Very Hard	280
10	SM, SC, CL, ML, MH, OL	Hard (Slippery)	130
11	SM, SC, CL, ML, MH, OL	Very Hard (Slippery)	280
12	CH, OH	Hard	130
13	CH, OH	Very Hard	280
14	CH, OH	Hard (Slippery)	130
15	CH, OH	Very Hard (Slippery)	280
16	PT	Dry Peat	40
17	GW, GP, GM, HC, Rock	Dry Loose Surface Road	300
18	GW, GP, GM, HC, Rock	Wet Loose Surface Road	300
19	NO-GO	Swamps, Bogs, Etc.	10
20	Concrete, Asphalt	Dry Pavement	600
21	Concrete, Asphalt	Wet Pavement	600
22	SM, SC, CL, ML, CH, MH, OL, OH	Brushland - Medium	80
23	SM, SC, CL, ML, CH, MH, OL, OH	Brushland - Hard	280
24	SM, SC, CL, ML, CH, MH, OL, OH	Brushland – Medium (Slippery)	80
25	SM, SC, CL, ML, CH, MH, OL, OH	Brushland - Hard(Slippery)	280
26	Water w/ (Silts and Clays) Bottom	Depth 16 inches	25
27	Water w/ (Silts and Clays) Bottom	Depth 33 inches	25
28	Water w/ (Silts and Clays) Bottom	Depth 60 inches	25
29	Water w/ (Bedrock, Gravel, Paved) Bottom	Depth 16 inches	300
30	Water w/ (Bedrock, Gravel, Paved) Bottom	Depth 33 inches	300

Table 4. The UAMBL Terrain Codes for the Libnrmm Implementation of STNDMob.

Terrain code	Soil Type	Veg. code	Cone Index 0-6 inch	Cone Index 6-12 inch	Description
0	7	0	300	300	default
1	2	0	300	300	asphalt
2	7	0	300	300	packed soil or dirt road
2	10	0	300	300	packed soil or dirt road. Used stone for SMC
3	6	0	80	80	soft sandy soil. Used sand for SMC
4	0	0	0	0	impassable deep water
5	7	0	100	100	passable shallow water
6	7	0	25	80	Muddy soil
7	7	0	25	300	Muddy road
8	7	0	100	100	slick ice surface. Ice for SMC
9	12	2	25	50	Impassable swamp in OTB
10	12	2	100	100	forested area in OTB
11	0	0	0	0	railroad with US specifications
12	0	0	0	0	railroad with European specs
13	2	1	300	300	small rocks <= 18 in high
14	2	2	300	300	large boulders 6 ft high
15	7	2	25	5	terrain that is not traversable
16	6	0	80	80	Poorly graded/uniform sands gravelly sand mix
17	7	0	80	80	Silty sand/silty gravelly sands
18	8	0	100	100	Clayer sands/clayey gravelly sands
19	9	0	75	75	Silts/Very fine sands
20	10	0	150	150	Low plasticity clays
21	12	0	150	150	Highly plastic clays and sandy clays
22	9	2	100	100	Soil in and around orchard
23	9	1	100	100	Soil in and around vineyard
24	7	0	300	300	Soil in and around urban area
25	7	0	300	300	Soil in and around town area
26	11	1	25	75	Passable swamp
27	7	0	300	300	Soil in and around farm buildings - not cultivated fields
28	7	0	300	300	Pipeline

There are 23 "HGTM soil types" of interest shown in Table 5 and their relation to other model representations. Because the terrain database must be capable of representing all-season conditions, several classes of roads were added. These are listed as types 17, 18 and 21- 23 in Table 5. This allows us to differentially apply the seasonal changes to other trafficable terrain types, specifically, to pack, plow or traffic the snow based on road classification.

Table 5. Soils Types for Different Models or Databases.

HGTM Soil Type	Libsoilmobility Index	USCS soil type	OOS - EDCS SOIL_TYPE USCS Soil type enumerations and TERRAIN_ROUTE_TYPE[1]	NRMM USCS soil and road types and (NRMM soil group code)
1	1	GW	GW	GW (6)
2	2	GP	GP	GP (6)
3	3	GM	GM	GM (4)
4	4	GC	GC	GC (1)
5	5	SW	SW	SW (6)
6	6	SP	SP	SP (6)
7	7	SM	SM	SM (4)
8	8	SC	SC	SC (1)
9	9	ML	ML	ML (3)
10	10	CL	CL	CL (3)
11	11	OL	OL	OL (3)
12	12	CH	CH	CH (2)
13	13	MH	MH	MH (2)
14	14	OH	OH	OH (2)
15	15	Pt	PT	Pt (7)
			ML_AND_CL	MLCL (3)
			SM_AND_SC	SMSC (4)
			EVAPORITES	
				GMGC (4)
16				Rock (5)
17			SECONDARY_ROAD	Secondary
18			PRIMARY_ROAD	Primary
			SUPER_HIGHWAY	Super Highway
19 - Shallow water				
20 - Deep water				
21 – Constructed, well maintained gravel road with well drained, good gravel surface				
22 – Constructed, marginal gravel road (constructed, but not always maintained or well drained)				
23 – "Two-Track" road/trail, made of natural soil material (not constructed - but compacted from traffic)				

DRAINAGE INDEX

Drainage index, table 6, was initially described by Bullock [3] as a wetness index, it is an indication of how easily the soil can dry out or become saturated based on drainage effects, cone index is directly related to soil moisture. These correspond to the EDCS attribute EAC_SOIL_WETNESS_CATEGORY enumerations.

Table 6. Drainage Index Categories [3].

Wetness Index	Potential Wetness	Depth to Water Table	Depth of Wetting	General Characteristics of Sites	EDCS Attribute Symbolic Constant: EAC_SOIL_ WETNESS_CATEGORY (corresponding enumerations)
0	Arid	Indeterminable	Less than 1 ft	Located in desert regions.	PERENNIALLY_DRY
1	Dry	Indeterminable	1- 4 ft	Steeply sloping, denuded or severely eroded and gullied.	
2	Average	More than 4 ft	More than 4 ft	Well-drained soil with no restricting layers or pans; fair to good internal and external drainage. Slope may be flat to steep.	MOIST
3	Wet	1- 4 ft	To water table	Soil not well drained. Restricting layers or deep pans may be present. May occur at base of slopes, on terraces, upland flats, or bottom lands.	WET
4	Saturated	Less than 1 ft	To water table	Sites waterlogged of flooded at least part of the year. Bottomlands subject to frequent overflow. Upland with poor drainage or shallow pans. Slopes with very poor drainage.	SATURATED
5	Saturated	Zero (surface)	Com- plete	Areas perennially waterlogged. No change in water content or soil strength.	WATERLOGGED

SLOPE AND ASPECT CLASSES

Aspect (or azimuth) affects the amount of incident solar radiation thus influencing soil drying or snow melting. Aspect categories based on discussions with subject matter experts led to the selection of 22.5 degree increments with North centered in the most northern range (16 categories). Slope categories based on vehicle mobility analyses [6, 7] are shown in Table 7, along with the representative value used in the terrain state analysis by FASST [8]. However, for the real-time simulator, the impact of slope on vehicle performance is explicitly calculated by the vehicle dynamics code, and what is needed here is for the effect of slope on terrain properties, specifically, the spatial distribution of snow cover. Analysis using an analytical model of snowmelt and accumulation, including solar energy input, led to the combination of slope and azimuth shown in Figure 2 and in Table 8, to account for the spatial distribution of snow and freeze/thaw.

Table 7. Mobility Slope Categories.

Category index	Range (%)	Value used in Terrain state analysis (%)
0	0-2	1
1	>2 & <=5	3.5
2	>5 &<=10	7.5
3	>10 & <=20	15
4	>20 & <=40	30
5	>40 & <=60	50
6	>60	?

Slope	Class										
0 - 3	0										
3 - 7	1	5	7	8	10	14	18	20	21	23	
7 – 10.5	2	5	7	8	11	15	18	20	21	24	
10.5 - 15	3	6	7	9	12	16	19	20	22	25	
≥15	4	6	7	9	13	17	19	20	22	26	
	0 36 72 108 144 180 216 252 288 324 360										
Azimuth											

Figure 2. Graphical Representation of the Slope and Aspect Classes Used in the Terrain Code for Spatially Distributing Snow Properties.

Table 8. Slope/Aspect Classes.

Slope/ Aspect Class	Slope range (degrees)	Azimuth range (degrees)	Slope/ Aspect Class	Slope range (degrees)	Azimuth range (degrees)
0	≥ 0 and < 3	0 to 360	14	≥ 3 and < 7	≥ 180 and < 216
1	≥ 3 and < 7	≥ 0 and < 36	15	≥ 7 and < 10.5	≥ 180 and < 216
2	≥ 7 and < 10.5	≥ 0 and < 36	16	≥ 10.5 and < 15	≥ 180 and < 216
3	≥ 10.5 and < 15	≥ 0 and < 36	17	≥ 15	≥ 180 and < 216
4	≥ 15	≥ 0 and < 36	18	≥ 3 and < 10.5	≥ 216 and < 252
5	≥ 3 and < 10.5	≥ 36 and < 72	19	≥ 10.5	≥ 216 and < 252
6	≥ 10.5	≥ 36 and < 72	20	≥ 3	≥ 252 and < 288
7	≥ 3	≥ 72 and < 108	21	≥ 3 and < 10.5	≥ 288 and < 324
8	≥ 3 and < 10.5	≥ 108 and < 144	22	≥ 10.5	≥ 288 and < 324
9	≥ 10.5	≥ 108 and < 144	23	≥ 3 and < 7	≥ 324 and < 360
10	≥ 3 and < 7	≥ 144 and < 180	24	≥ 7 and < 10.5	≥ 324 and < 360
11	≥ 7 and < 10.5	≥ 144 and < 180	25	≥ 10.5 and < 15	≥ 324 and < 360
12	≥ 10.5 and < 15	≥ 144 and < 180	26	≥ 15	≥ 324 and < 360
13	≥ 15	≥ 144 and < 180			

CANOPY

The amount and type of vegetation canopy will have an effect on the amount of solar energy that is imposed on the ground surface, impacting surface drying, freeze/thaw and snowmelt. The OpenFlight format allows each polygon to have a ground material type; the classes of interest (those indicating some type of vegetation) are shown in Table 9. These canopy indices are combined with the other terrain codes to get the actual surface conditions. OpenFlight allows other codes (ESID, which are extension of the DFAD codes developed by Evans and Sutherland), but these can generally be mapped to the DFAD codes [9].

Table 9. Vegetation and Canopy Codes.

HGTM		OpenFlight	
Index	Canopy description		DFAD FIC Classes
0	Open	902	PHYSIOGRAPHY - Soil (general)
0	Open	906	Sand/Desert
0	Open	907	Sand Dune/Sand Hill
1	Mixed light	908	Marsh, Wetland, Swamp, Bog
0	Open	909	Rice Field
0	Open	912	Rocky rough surface
0	Open	913	Dry Lake
0	Open	916	Cleared Ways
0	Open	934	Salt Pan
1	Mixed light	950	Vegetation (general)
2	Deciduous light	951	Orchard/Hedgerow
3	Deciduous dense	952	Trees, Deciduous
4	Conifers dense	953	Trees, Evergreen
5	Mixed Dense	954	Trees, Mixed (Evergreen and Deciduous)
0	Open	955	Tundra
2	Deciduous light	956	Vineyard/Hops
6	Non-canopy Trail		Trails without a canopy
7	Canopied trail		Trails with a canopy

Trails (a soil or improved non-paved roadway) with and without a canopy are added here to take advantage of two free indices, and to allow differentiation of soils which make up a trail (soils on trails maybe of the same type as others in the area, but have a different terrain condition (stronger, packed snow, etc). A little information is lost regarding the amount of canopy, but the ability to differentiate a trail from surrounding soil is gained.

ELEVATION AFFECTS
Elevation can influence the amount of precipitation an area receives, and there are models to estimate this effect, snowfall is particularly affected. Elevation is not included in the HGTM terrain surface type, but for ranges of elevation (dependant on the weather condition scenario or measured data) multiple sets of the HGTM terrain mechanics tables can be created.

RESULTING HGTM TERRAIN SURFACE TYPE AND TERRAIN MECHANICS TABLE
The parameters that make up the HGTM terrain surface type are:

Soil Type (23)	5 bits
Drainage indices (6)	3 bits
Slope and Aspect (27)	5 bits
Canopy indices (8)	3 bits
	16 bits

Each terrain polygon is assigned a terrain code by combining the bits for each class or index into a hexadecimal number. To accomplish this, software was developed which interfaces to the OpenFlight API. It queries every polygon in the OpenFlight database and checks for the center of the polygon, while also determining the aspect (based upon the calculated normal of the polygon) and the slope. Using the center of the polygon, tables containing the vegetation types, soil types and drainage characteristic are queried. These five values are then written into the polygon's record according to Tables 5,6,8 and 9. This modified OpenFlight database is then used during the real-time simulation and is queried for the surface type information every time step.

The HGTM terrain properties table is configured to be easily developed or modified using a spreadsheet. A list of all the HGTM terrain surface types is obtained from the OpenFlight database, within specified elevation ranges. Table 10 shows how the hexadecimal HGTM terrain surface code is translated in the spreadsheet.

Table 10. Conversion of the Hexadecimal Code to HGTM Surface Types/Classes.

		Bit Code				**Decimal Equivalents**				**HGTM Surface Type/class**			
Hexi-decimal	Decimal	Soil code (5 bits)	Wetness Index (3 bits)	Slope-Aspect class (5 bits)	Canopy Index (3 bits)	Soil code	Drainage	Slope-Aspect	Canopy	Soil code	Drainage	Slope-Aspect	Canopy
1B90	7056	00101	011	10010	000	5	3	18	0	SW	Wet	19	Open
1A00	6656	00101	010	00000	000	5	2	0	0	SW	Avg	1	Open
1B01	6913	00101	011	00000	001	5	3	0	1	SW	Wet	1	Mixed Light
B09	2825	00001	011	00001	001	1	3	1	1	GW	Wet	2	Mixed Light
B0B	2827	00001	011	00001	011	1	3	1	3	GW	Wet	2	Decid Dense
2B0B	11019	01011	011	00001	011	11	3	1	3	OL	Wet	2	Decid Dense
3B15	15125	01101	011	00010	101	13	3	2	5	MH	Wet	3	Mixed Dense
315	789	00010	011	00010	101	2	3	2	5	GP	Wet	3	Mixed Dense
414	1044	00010	100	00010	100	2	4	2	4	GP	Sat_4	2	Conif Dense

These terrain codes are permanent fixtures of the terrain and are used to assign terrain strength properties to the polygon by linking to a terrain mechanics table which is based on the season or weather, time of year, or even time of day. Table 11 shows the file format for terrain properties indexed with the hexadecimal code. These terrain mechanics properties are used in the calculation of the forces at the vehicle-terrain interface as illustrated in Figure 1. Because of this modular set up of the interface and terrain mechanics table, the tables can be easily changed to accommodate different parameters as the interface code is updated to more sophisticated vehicle-terrain models.

An application of this methodology for the a seasonal terrain database; the Vermont National Guard's Ethan Allen Firing Range in Northern Vermont, is presented in Shoop, et al, [10].

Table 11. Sample Terrain Properties Table with 3 Ranges of Elevation.

Elevation = <500

Hex code	Decimal code	Terrain Surface Condition	Soil Type	Soil Moisture code	RCI 0-6	RCI 6-12	Surface Cover Depth	Snow Density	Frost Depth	Thaw Depth
1B90	7056	NCG	SW	NOR	150	300	0	0	0	0
1A00	6656	NCG	SW	NOR	150	300	0	0	0	0
1B01	6913	NCG	SW	NOR	150	300	0	0	0	0
B09	2825	NCG	GW	NOR	150	300	0	0	0	0
B0B	2827	NCG	GW	NOR	150	300	0	0	0	0
2B0B	11019	SFG	OL	SLP	100	200	0	0	0	0
3B15	15125	SFG	MH	SLP	80	200	0	0	0	0
315	789	NCG	GP	NOR	250	300	0	0	0	0
Elevation < 1500										
1B90	7056	SS	SW	AVG	150	300	5	0.3	30	0
1A00	6656	SS	SW	AVG	150	300	10	0.3	30	0
1B01	6913	SS	SW	AVG	150	300	15	0.3	30	0
B09	2825	FCG	GW	AVG	150	300	0	0	30	2
B0B	2827	SS	GW	AVG	150	300	10	0.3	30	0
2B0B	11019	SS	OL	DRY	80	200	10	0.3	0	0
3B15	15125	FFG	MH	SAT	300	200	0	0	30	0
315	789	FCG	GP	SAT	250	300	0	0	30	0
Elevation ≥ 1500										
1B90	7056	SS	SW	DRY	300	300	20	0.25	30	0
1A00	6656	SS	SW	DRY	300	300	30	0.25	30	0
B09	2825	SS	GW	DRY	300	300	20	0.25	30	0
2B0B	11019	SS	OL	DRY	300	300	10	0.25	30	0
3B15	15125	SS	MH	DRY	300	300	5	0.25	30	0
315	789	SS	GP	DRY	300	300	5	0.25	30	0

SUMMARY

A method of linking current terrain conditions to an OpenFlight database, without the need to recompile is presented. The current terrain conditions data supports high-resolution terrain interaction of a ride motion simulator. Implementation of terrain related attributes to support both the simulator and SAF models is illustrated in this paper.

ACRONYMS

CCTT	Combined Arms Tactical Training System
CTDB	Compact Terrain Database
DFAD	Digital Feature Analysis Database
DTSIM	Dynamic Terrain Simulator
EDCS	Environmental Data Coding Specifications
EnviroFed	Environment Federation
ERDC-GSL	Engineer Research and Development Center, Geotechnical and Structures Laboratory
HGTM	US Army Science and Technology Objective #IV.GC.2003.01, "High Fidelity Ground Platform and Terrain Modeling" project
JSAF	Joint Semi-Automated Forces
JVB-OTB	The Joint Virtual Battlespace version of OTB
OTB	OneSAF Testbed Baseline
OOS	OneSAF Objective System
NRMM	NATO Reference Mobility Model
SAF	Semi-Automated Force
SIMNET	Simulator Networking
STNDMOB	Standard mobility, a set of code based on NRMM, which predicts the maximum speed possible for a ground vehicle for a given set of terrain properties.
STO	Science and Technology Objective
TARDEC	US Army Tank-Automotive Research and Development Center

UAMBL   Unit of Action Mounted BattleLab
USCS   Unified Soil Classification System

LITERATURE CITED

1. Nunez, P., A. Reid, R. Jones, and S. Shoop (2002) A Virtual Evaluation Suite for Military Ground Vehicle Dynamic Performance and Mobility, SAE Truck and Bus Conference, Nov. 02, SAE paper 2002-01-3049.
2. Richmond, P. W., R. Jones, D. Creighton, and R.B. Ahlvin (2004) Estimating Off-road Ground Contact Forces for a Real Time Motion Simulator, SAE Commercial Vehicle Engineering Congress & Exhibition, SAE paper 2004-01-2643, Also in SAE Special Publication on Advancements in Air Brake Systems, Truck Suspensions & Military Vehicle/Terrain Interface, SP-1905.
3. Bullock, C.D. (1994) Methodology for the development of inference algorithms for worldwide application of interim terrain data to the NATO reference mobility model. Technical Report GL-94-37, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg MS.
4. Birkel, P. (2003) Terrain Trafficability in Modeling and Simulation. SEDRIS Technical Paper 2003-1
5. Mason, G., R. Ahlvin, and J.Green (2001) Short-Term Operational Forecasts of Trafficability,US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS. ERDC/WES TR-01-22.
6. Mason, G., R. Ahlvin, and A. Baylot (2001) Advanced Movement Representation in High Resolution Models. March 2001, Simulations Interoperability Standards Organization (SISO), Paper Number 00S-SIW-123, Orlando Fl.
7. Mason, G. L., and J. Farr (1990) "Engineer Model Improvement Program; Report 1 Standardization of Terrain Data for the Vector-in-Command and Engineer Functional Area Models", Technical Report GL-90-9, September 1990, USAEWES, Vicksburg
8. Frankenstein, S. and G. G. Koenig (2004) Fast All-season Soil Strength (FASST), US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS. ERDC/CRREL SR-04-1.
9. MIL-PRF-89005 (1994) Digital Feature Analysis Database (DFAD) Levels 1/2, 5 August 1994 [supersedes both PS/1CE/200 and PS/1CG/200, NOT APPROVED FOR ACQUISITION PURPOSES]
10. Shoop, S.A., B. Coutermarsh, and A. Reid (2004) All-Season Virtual Test Suite for a Real-Time Simulator SAE Commercial Vehicle Engineering Congress & Exhibition, SAE paper 2004-01-2644, Also in SAE Special Publication on Advancements in Air Brake Systems, Truck Suspensions & Military Vehicle/Terrain Interface, SP-1905.